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Low NOx, High Efficiency Multistaged Burner Gaseous Fuel Results

Acurex Corp., Research Triangle Park, NC

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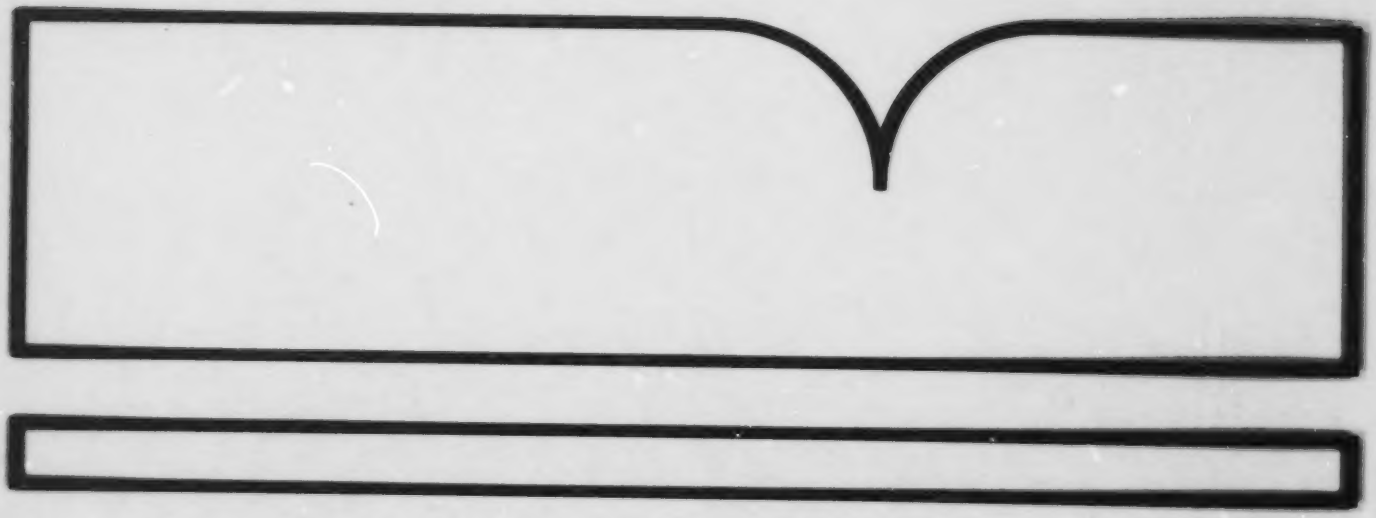

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16. ABSTRACT The paper discusses the evaluation of a multistaged combustion burner design on a 0.6 MW package boiler simulator for in-furnace NOx control and high combustion efficiency. The adiabatic precombustion chamber burner has been reduced in size by a factor of about 2. Natural gas, doped with ammonia to yield a 5.8% fuel nitrogen content, was used to simulate high nitrogen content fuel/waste mixtures. A burner baseline NO emission of 315 ppm (measured dry, corrected to zero % O2) was measured, compared with an emission of over 1000 ppm estimated for a conventional unstaged burner. Both deep air staging, resulting in a three-stage configuration, and boiler front wall fuel staging of undoped natural gas, yielding four stoichiometric zones, reduced the baseline NO emission by about 50% to 160 ppm, meeting the program goal. However, deep air staging resulted in the entire front end of the boiler being fuel-rich and required penetrations into the boiler for staged air injection. The fuel staging results, on the other hand, required no boiler penetrations and only a small fuel-rich flame core in the boiler. Further, sufficient air for complete oxidation of the primary combustion products was provided at the burner exit, prior to staged fuel and air injection in the boiler, in the fuel staging tests.

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Burners	Stationary Sources	13A
Nitrogen Oxides	Multistaged Burners	07B
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Low NO_x, High Efficiency Multistaged Burner: Gaseous Fuel Results

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A multistaged combustion burner design is being evaluated on a 0.6 MW package boiler simulator for in-furnace NO_x control and high combustion efficiency. A low NO_x precombustion chamber burner has been reduced in size by approximately a factor of two (from a 600 ms first-stage residence time to 250 ms), and, for additional NO_x control, coupled with [1] air staging, resulting in a three-stage configuration, and [2] natural gas fuel staging, yielding up to four stoichiometric zones. Natural gas, doped with ammonia to yield a 5.8 percent fuel nitrogen content, was used to simulate a high nitrogen content fuel/waste mixture. In low NO_x burner baseline tests, without advanced staging, a 315 ppm NO emission (measured dry, corrected to zero percent O_2) was measured, compared with an emission of 1000 ppm measured using a conventional, unstaged burner. Both of the multistaged combustion modifications for additional NO_x control reduced NO emissions by an additional 50 percent, to 160 ppm meeting the program goal. However, air staging application resulted in the entire front end of the boiler being fuel-rich, whereas fuel staging, or reburning, in the boiler required only a small fuel-rich flame core in the boiler. Further, no boiler penetrations were necessary with reburning modification, as staged fuel and air were injected through the boiler front wall; access for burnout air injection deep into the boiler was necessary for the air staging modification. Thus, the four-stage configuration, combining the precombustion chamber burner and reburning, appears to be the most promising approach for minimizing NO emissions and maximizing primary fuel/waste destruction.

INTRODUCTION

The family of nitrogen oxide compounds, including nitric oxide (NO) and nitrogen dioxide (NO_2), is generally referred to as "NO_x." These NO_x are formed during the combustion of coal, oil, and natural gas by the reduction and oxidation of molecular nitrogen (N_2) and nitrogen contained in the fuel. NO_2 is a poisonous gas that the United States Environmental Protection Agency (EPA) has designated as a criteria pollutant because of its human health effects [1, 2]. Further, NO_x are known to contribute to the formation of photochemical oxidants and are precursors, along with sulfur oxides (SO_x), of acid precipitation. Two more areas of concern are emerging in regard to NO_x levels in the atmosphere. First, forest damage, reported to be extensive in the Federal Republic of Germany [3], has been linked with increasing NO_x levels. Second, increasing levels of atmospheric nitrous oxide (N_2O) have been measured, levels that have been predicted to contribute to both a decline in the abundance of stratospheric ozone and an increase in climatic warming

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[4]. Studies of N_2O and NO concentrations in experimental flames and in flue gases have shown that a strong correlation exists between these two gases formed in combustion processes.

The EPA estimates that about 20 million tons (18,000 Gg) of NO_x are emitted annually from stationary and mobility sources in the United States. Unlike SO_x emissions, NO_x emissions have been increasing [5]. Coal- and oil-fired utility and industrial boilers account for over half of the NO_x emissions. Only 15 percent of these stationary sources are regulated by EPA's New Source Performance Standards (NSPS) [6]; the remainder must be addressed with retrofit technologies if significant NO_x emission reduction is to be realized. Another NO_x control problem is posed by the potential of incinerating high nitrogen content wastes in industrial boilers. While incineration of these materials would not constitute a significant increase in the overall national NO_x emission level, individual plant emissions may be sufficient to result in a local NO_x problem and, thus, prevent on-site incineration from being permitted. With thermal destruction being an attractive alternative to landfill storage of wastes, there continues to be a need for developing high efficiency, low NO_x combustion technologies.

By far, the major portion of NO_x has been found to be NO. Much is known about the mechanisms of NO formation in flames, both from molecular nitrogen (source of thermal NO) and from fuel-bound nitrogen (source of fuel NO). Thermal NO can be reduced by decreasing peak flame temperatures. Fuel NO, not as strongly dependent on temperature, is very sensitive to reactant stoichiometry. Fuel-rich conditions promote Ni_2 formation over No formation. Laboratory studies and field test data have established the importance of fuel NO to the total emission of NO_x from residual fuel oil and coal flames. Therefore, minimizing NO_x formation in flames typically involves controlling air and fuel mixing rates to create fuel-rich reducing zones and extracting heat to reduce final oxidation temperatures.

To avoid the need for costly post-combustion NO_x removal, several in-furnace NO_x control strategies have been developed and applied to boilers. These include reduced air preheat, load reduction, low excess air, flue gas recirculation, overfire air, deep air staging, fuel staging (or reburning), and various low-NO_x burner systems [7], while NO_x emissions can be reduced by 20 to 80 percent using these technologies, from uncontrolled levels exceeding 1000 ppm for some high nitrogen content coals, application of these combustion modifications can result in reductions in combustion efficiency and increases in sooting and slagging in the boiler. This problem is of particular concern in the boiler co-firing of fuels and wastes, where high waste destruction efficiencies and minimal formation of other incomplete combustion products are of paramount importance. The purpose of this work is to investigate various multistaged combustion concepts for burning high nitrogen fuel/waste streams with low NO_x emissions and high combustion efficiency. Specifically, tests were designed to evaluate the use of a precombustion chamber burner, modified to reduce burner size, coupled with air or air/fuel staging. A NO_x emission of less than 0.2 lb (as NO_2)/10^6 Btu* (or approximately 175 ppm NO_x**) for firing gaseous and liquid fuels doped with up to 5 percent nitrogen (by weight) was targeted. In this paper pilot-scale test results with gaseous fuel firing are presented; results with fuel oil/pyridine firing are being published separately.

Before describing the experimental procedure and results, some background information is provided.

Precombustion Chamber Burner

The precombustion chamber burner is a staged combustion technology capable of achieving a NO_x emission of less than 0.1 lb (as NO_2)/10^6 Btu (or approximately 90 ppm NO_x), even with high nitrogen fuel firing [8]. It consists of a primary air and fuel injection system, a large refractory wall precombustion chamber, and a secondary air injection section. Fuel and primary air are injected with rapid mixing into the nearly adiabatic precombustion chamber with a first-stage stoichiometry of between 0.6 and 0.8.*** A residence time between 0.6 and 1.0 s allows for maximum reduction and conversion of fuel nitrogen species to N_2 in the fuel-rich precombustion chamber. First-stage combustion gas products exit the burner through a convergent section which minimizes both radiative heat loss to the boiler and back-mixing of the secondary air. The transition section between the burner and boiler is water-cooled to reduce combustion gas temperatures before final air addition. The precombustion chamber burner has been tested on a full-scale (16 MW_t) crude oil-fired steam generator used for thermally enhanced oil recovery (TEOR) in Kern County, CA [9]. A 30-day continuous monitoring test demonstrated the burner's ability to maintain a nominal NO_x emission of 70 ppm with a high combustion efficiency [10]. During burner optimization testing, NO_x, CO, and smoke emissions were measured over a range of first-stage stoichiometries. These data indicate the sensitivity of NO emission to first-stage stoichiometry and the good hydrocarbon burnout characteristics of the burner. Earlier pilot-scale tests firing nitrogen-free fuels suggest that the minimum NO_x level of about 50 ppm can be attributed to second-stage thermal NO formation.

A test designed to demonstrate the potential for using this burner for nitrogenous waste incineration was performed at EPA's Air and Energy Engineering Research Laboratory. A pilot-scale (0.6 MW) precombustion chamber burner was used to incinerate a surrogate nitrogenous waste mixture of 9.1 percent (by volume) pyridine in fuel oil. A NO emission of less than 100 ppm was maintained, with greater than six nines (99.9999 percent) destruction of the pyridine being achieved. The relative NO emissions with and without pyridine addition indicate that less than 1 percent of the fuel nitrogen was converted to NO. This preliminary result sparked interest in utilizing the precombustion chamber burner for high efficiency, low NO_x combustion.

However, while the precombustion chamber burner has been demonstrated successfully in pilot-scale and field tests, its large size makes it impractical for most boiler retrofit applications. Reducing the burner size results in insufficient first-stage residence time to fully convert the fuel nitrogen to N_2; hence, higher NO emissions result. Additional NO_x control can be achieved by further staging of the combustion process in the boiler.

Staged Combustion

The concept of staged combustion consists of injecting secondary air into the boiler downstream of the primary combustion zone, which is characterized by substoichiometric levels of combustion air. This concept may be employed by utilizing overfire air ports, secondary air injectors, or burners-out-of-service. In applications with a

* The current NSPS for large industrial boilers firing high nitrogen heavy fuel oil is 0.4 lb/10^6 Btu. This standard is under review. (1 lb/10^6 Btu = 0.43 kg/GJ.)

** All NO_x/NO emissions reported in this paper are referenced to a dry measurement corrected to zero percent O_2.

*** The stoichiometric ratio (SR), the actual air-to-fuel ratio divided by the theoretical air-to-fuel ratio, is used throughout this paper.

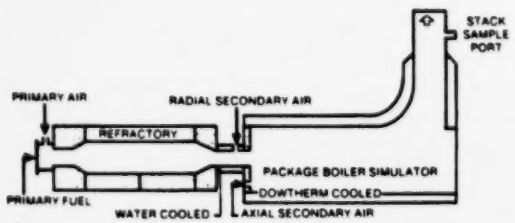
shortened precombustion chamber burner, further air staging would extend the fuel-rich first stage from the burner into the boiler.

Reburning

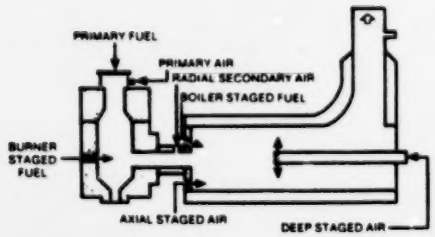
As many as 30 years ago, experimental results were available indicating that NO_x could be destroyed by reaction with hydrocarbon radicals. Early fundamental studies of NO_x destruction by injection of secondary fuel into the flame zone were performed by Wendt *et al.* [*11*] who coined the name "reburning" to describe the process. Concerted effort to develop reburning for application to boilers occurred in Japan during the late 1970's and early 1980's. The first reporting of these efforts was by Takahashi *et al.*, [*12*] documenting extensive laboratory-, pilot-, and full-scale evaluations of a fuel staging process they refer to as Mitsubishi Advanced Control Technology, or MACT.

Since 1982 EPA has carried out both in-house and extramural bench- and pilot-scale reburning tests. In-house experiments have focussed on natural gas and fuel oil reburning [*13-16*]. Significant findings include defining the dependence of reburn effectiveness on primary flame NO_x level, reburn zone stoichiometry, and reburn fuel nitrogen content. Fifty percent NO_x reduction is possible with 10 to 20 percent of the fuel used for reburning. At low primary NO_x levels, however, a nitrogen-free reburning fuel (such as natural gas) must be used to achieve 50 percent reduction. Tests have shown that reburning is effective over a wide range of temperatures and with relatively short reburning zone residence times (0.2 to 0.4 s).

In application with a shortened precombustion chamber burner, reburning would result in a four-stage combustion process. Because much of the primary fuel has been reduced prior to boiler entry, reburning might be applied from the front wall of the boiler. Such reburning application would simplify the boiler retrofit requirements by not requiring multiple boiler penetrations.



(a) Long, horizontal burner



(b) Short, vertical burner

Figure 1. Pilot-scale combustion research facility. The package boiler simulator has been fitted with a precombustion chamber burner and air and fuel staging ports.

EXPERIMENTAL PROCEDURE

The goal of this study is to minimize NO_x formation, with an emission target of 175 ppm or less, and maintain efficient incineration in the combustion of surrogate fuel/waste mixtures with up to 5 percent fuel nitrogen by using a precombustion chamber burner reduced in size by about half.

The unmodified facility, shown schematically in Figure 1a, is comprised of a precombustion chamber burner and a package boiler simulator. The precombustion chamber burner consists of a primary fuel and air injection module, two 0.89 m long spool modules with 0.51 m internal diameter, and a 0.33 m long convergent module. These burner modules have a thick refractory wall lining to minimize heat loss, maintaining the high temperatures that promote conversion of fuel nitrogen to N_2 under fuel-rich stoichiometries. To achieve rapid mixing in the precombustion chamber, the primary fuel is injected through a divergent nozzle and the primary air, which is not preheated, is passed through fixed swirl vanes. The convergent module minimizes back-mixing of combustion gas and radiation loss to the boiler. A water-cooled transition module, 0.25 m in internal diameter, cools the combustion gas before secondary air addition to minimize thermal NO generation. Primary fuel nitrogen is simulated by doping ammonia into natural gas or pyridine into distillate fuel oil. All of the results reported here are with the gaseous fuel.

The pilot-scale boiler simulator is rated at 0.9 MW thermal input. The boiler's radiant section is horizontal, 0.6 m in diameter, 3.0 m long, and cooled with Dowtherm G® heat transfer fluid. Combustion gas exits the boiler through a vertical stack. The boiler's front face has eight axial ports for addition of staged air.

The research facility was modified as shown in Figure 1b. The horizontal 2.62 m long precombustion chamber burner was replaced with a shorter 1.80 m long vertical burner. This shorter burner, with a nominal residence time of 250 ms, has all the essential design features of the long horizontal burner, which has a nominal residence time of 600 ms. The elbow section has a 5 cm diameter port for staging fuel into the burner. Two of the eight axial air ports on the boiler front face were modified to provide ports for staging fuel into the boiler at an angle of 45 degrees. This design allows for reburning application from the boiler front face, the aerodynamic separation of the fuel-lean and fuel-rich zones in the boiler. The end plate of the boiler has been modified to allow the insertion of a water-cooled boom for deep staging of air into the boiler.

The experimental facility is designed for independent control and measurement of each fuel, fuel dopant, and air stream. Stack, gas speciation is measured by a continuous emissions monitoring system. NO and NO_2 are measured by chemiluminescence. Spot-check measurement of NO_x indicated that NO emissions accounted for over 95 percent of the exhaust NO_x emissions. In this paper only NO measurements are reported.

A North American Scotch-type package boiler (N.A.) was used to provide conventional burner results to be compared with the multistaged burner results. This boiler is a three-pass unit with a continuous service rating of 0.3 kg of steam per second (2400 lb/hr). Its size and thermal characteristics are nearly identical to those of the package boiler simulator [*9, 10*].

Evaluated were burner baseline performance and burner operation with various air staging and fuel staging NO_x controls. The parameters affecting the NO_x emissions from the facility without additional NO_x controls are fuel nitrogen content, combustion gas residence time in the precombustion chamber, first-stage stoichiometry, and exhaust stoichiometry. The residence time of combustion

gas in the burner depends on precombustion chamber length, load, and stoichiometry. The nominal load was 0.6 MW. The exhaust stoichiometry was kept at a nominal value of 15 percent excess air, as per commercial boiler practice. Nominal fuel nitrogen content was 5.8 percent (by weight), as ammonia doped in natural gas.

BURNER BASELINE CHARACTERIZATION

During burner baseline characterization tests, the effects of burner length, first-stage stoichiometry, excess air, load, and fuel nitrogen content on NO emissions were studied. Three burner configurations, two with a horizontal orientation and residence times of 600 and 350 ms and one with a vertical orientation and a residence time of 250 ms, were evaluated, and compared to data using a conventional, unstaged burner.

Burner Stoichiometry Variation

First-stage stoichiometry was varied by changing the primary and secondary air inputs while maintaining an overall 15 percent excess air. The results of these tests are plotted in Figure 2. Two curves (square and triangle symbols) in the figure correspond to the long (two spool modules) and short (one spool module) configurations of the unmodified facility (Figure 1a). The third curve (circle symbols) corresponds to the facility configuration used in the rest of this study (Figure 1b). The curves indicate a strong sensitivity of stack NO to changes in first-stage stoichiometry. For the long, horizontal burner configuration, with a residence time of 600 ms, the minimum stack NO concentration was 60 ppm at a primary fuel nitrogen content of 0.66 percent. With the short, horizontal burner configuration, with a residence time of 350 ms, the minimum NO stack concentration rose to 200 ppm at the same fuel nitrogen content. In the vertical burner, when firing a fuel with 5.8 percent fuel nitrogen, a minimum NO emission of 315 ppm at a first-stage stoichiometry of 0.78 was achieved. Thus, additional combustion modifications are necessary to achieve the program goal of 175 ppm maximum NO emission with the new burner configuration.

Excess Air Variation

The effect of excess air variation on stack NO is shown in Figure 3. Excess air had a much stronger effect in the unstaged North American burner tests than in the low NO_x burner tests, as expected. While reducing excess air did provide some NO reduction, maintaining an exhaust excess air level of 15 percent is important for achieving high combustion efficiency.

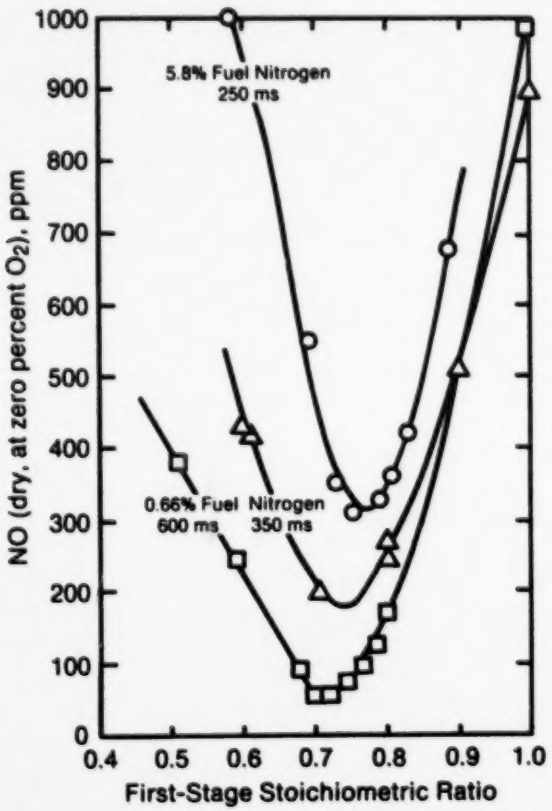


Figure 2. Effect of burner size and fuel nitrogen content. The square and triangle symbols correspond to test data with the long and short (respectively) horizontal burner firing natural gas containing 0.66 percent nitrogen as ammonia. The circle symbols represent data with the vertical burner firing natural gas containing 5.8 percent nitrogen as ammonia.

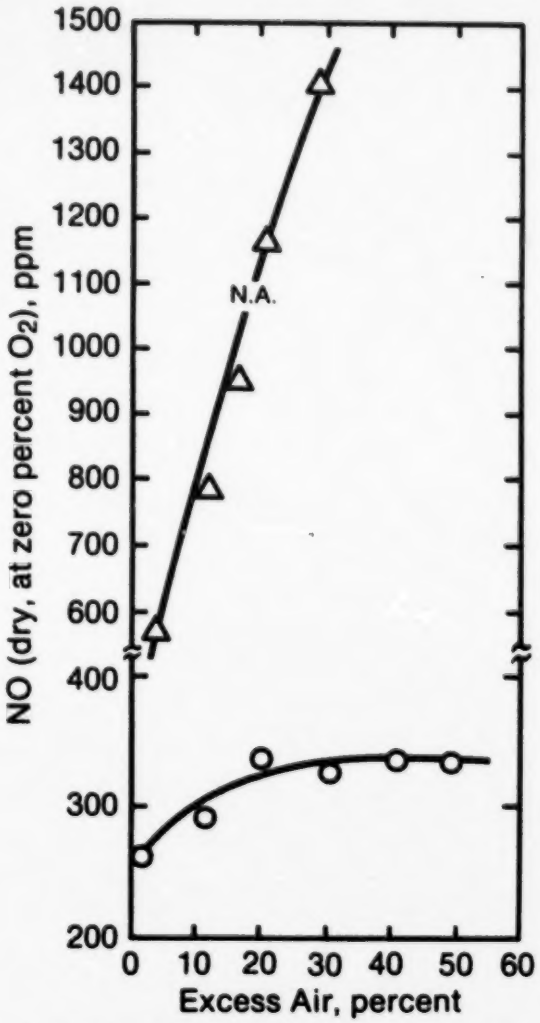


Figure 3. Excess air variation results for the unstaged North American burner and the low NO_x burner.

Load Variation

The effect of load reduction on stack NO is shown in Figure 4. With the unstaged burner, NO emissions were reduced only slightly with burner derating, due to decreased air-fuel mixing intensity. However, with the low NO_x burner, the effect was much greater because load reduction corresponds to an increase in first-stage residence time and, thus, a decrease in NO emission. As load was decreased from a nominal condition of 0.6 MW to about 65 percent of nominal, the stack NO concentration dropped from 315 to 260 ppm in the low NO_x burner tests. Reducing load by 35 percent increased the residence time from 250 ms to about 385 ms. However, boiler steam requirements may make load reduction an impractical means of NO_x control.

Fuel Nitrogen Variation

The effect of fuel nitrogen variation, which is analogous to varying the amount of nitrogenous waste (ammonia-doped natural gas with 6 percent nitrogen) co-fired with a nitrogen-free fuel (natural gas), is shown in Figure 5. Data are plotted for the full range of co-firing conditions, from 100 percent fuel to 100 percent surrogate waste. Exhaust NO level increased with increasing fuel nitrogen content in the fuel/waste stream, as expected, with a much greater sensitivity observed in the conventional North American burner tests. These results demonstrate the precombustion chamber burner's ability to reduce fuel nitrogen to molecular nitrogen, even with its reduced size (250 ms). The full size (600 to 800 ms) precombustion chamber burner produces NO emissions even less sensitive to fuel nitrogen content [8].

AIR STAGED NO_x CONTROLS

During air staged NO_x control tests, the effect of moving the location of secondary air addition, from the radial ports in the transition section to the axial and deep staged ports in the boiler, was examined. The secondary air was distributed between radial and axial locations in one series of staging tests and between radial and deep staged ports (located 132 cm from the boiler front face) in a second series of tests. A water-cooled boom, aligned with the

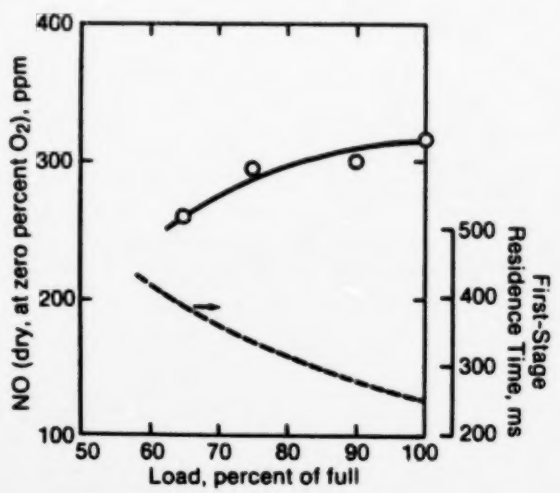


Figure 4. Load variation results for the low NO_x burner.

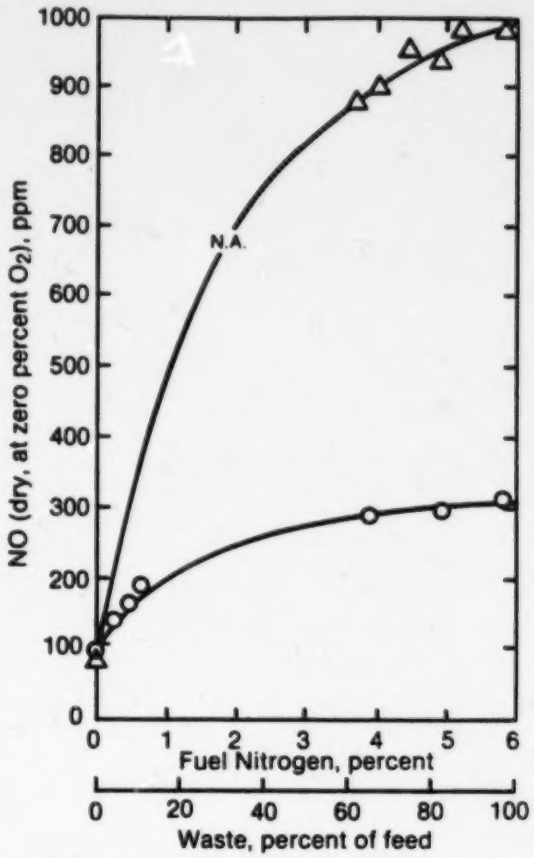


Figure 5. Fuel/waste nitrogen variation results for the unstaged North American burner and the low NO_x burner.

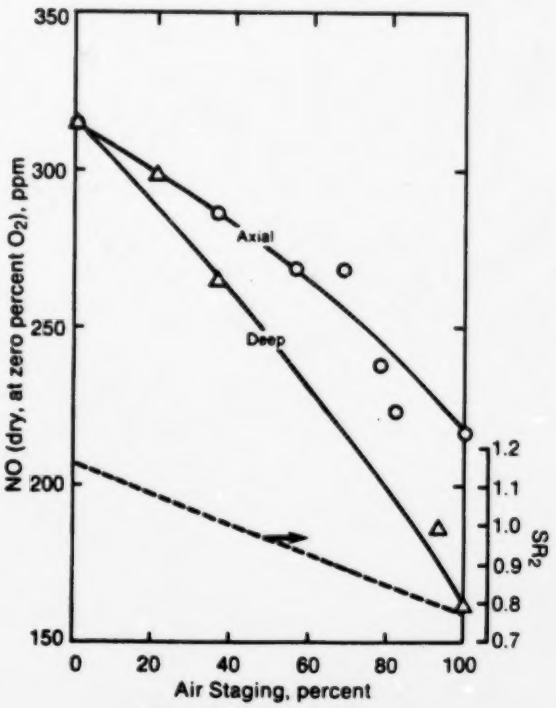


Figure 6. Air staging results.

centerline of the boiler, was used to supply the deep staged air. First-stage stoichiometry was optimized for each test condition.

Test results for the two cases of secondary air staging in the boiler are shown in Figure 6. The axial air staging results show a drop in minimum NO concentration from 315 ppm with no staging to 220 ppm with 100 percent of the secondary combustion air moved from the radial injectors to the axial injectors. The temperature of the combustion gases is higher in the transition section than in the boiler; also, the mixing of secondary air and combustion gas is more rapid when the secondary air is added radially into the transition section. Hence, more thermal NO is generated and more fuel nitrogen species fragments are oxidized with radial air addition into the transition section than with axial addition into the boiler. Similarly, lower temperatures in the boiler at the deep staged air location and longer fuel-rich zone residence time result in a lower NO emission when the secondary air is deep staged. With all of the secondary air being added from the deep staged location, the minimum NO level was 160 ppm.

Based on the test results just described, the deep staging of secondary air is an effective means of minimizing NO emissions. However, such staging may lead to burnout problems, which is of great concern when co-firing waste. Extending the fuel-rich zone from the precombustion chamber into the boiler exposes the reducing combustion gases to the cool boiler walls, which may result in slagging and/or sooting. Further, the lower combustion gas temperatures in the boiler slow the fuel-rich nitrogen kinetics.

FUEL STAGED NO, CONTROLS

During fuel staged NO, control tests, the effect of diverting part of the primary fuel to staged locations in the burner and boiler was studied. The stage fuel was natural gas, with no ammonia dopant. The first-stage stoichiometry was optimized with respect to NO emission. In the case of fuel staging in the burner, the secondary natural gas was added, using a water-cooled boom, down the centerline of the boiler; secondary air was added axially into the boiler to allow sufficient fuel-rich zone residence time. In the case of fuel staging in the boiler, the secondary natural gas was added at an angle of 45 degrees, using two water-cooled booms, from ports in the boiler front face. Secondary air to complete primary fuel combustion was added radially into the transition section, while burnout air for secondary fuel combustion was added axially into the boiler, using six axial ports on the boiler front face.

Burner Fuel Staging Results

Holding total load constant, fuel was diverted from the primary fuel injector to a secondary injector near the precombustion chamber exit (see Figure 1b), thus creating two stoichiometric zones in the burner in addition to the burnout zone in the boiler. The staged fuel, undoped natural gas, provides a burst of hydrocarbon radicals that accelerate the reduction of primary fuel nitrogen to N_2 prior to secondary air injection. Secondary air was injected through the axial injectors. The results, plotted in Figure 7, show a decrease in NO emission with increasing fuel staging. Two effects contribute to this decrease in NO emissions with fuel staging: (1) fuel nitrogen reduction mechanisms are accelerated due to increased radical concentrations, and (2) combustion gases from the high nitrogen content primary fuel are diluted by the combustion gases from the nitrogen-free secondary fuel. With 35 percent of the fuel staged, the exhaust NO levels decreased

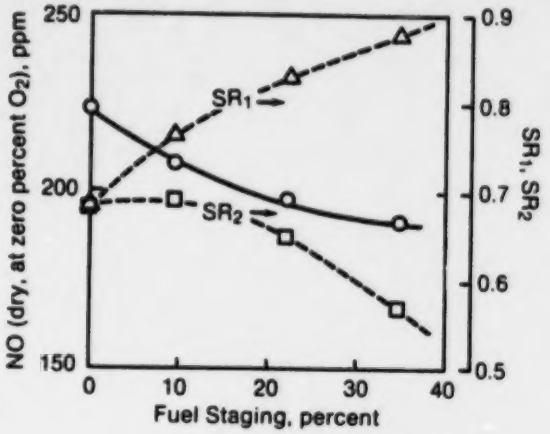


Figure 7. Burner fuel staging results.

to 190 ppm, from 220 ppm at zero percent staging (and axial secondary air addition). The figure also shows that the optimum first-stage burner stoichiometry (SR_1) increases with increasing fuel staging, while the optimum second-stage burner stoichiometry (SR_2) decreases slightly. This result is consistent with kinetic model predictions of optimum stoichiometries for the two burner stages. A first-stage stoichiometry of 90 percent theoretical air should result in a higher destruction efficiency of the primary fuel/waste stream than with a more fuel-rich first stage.

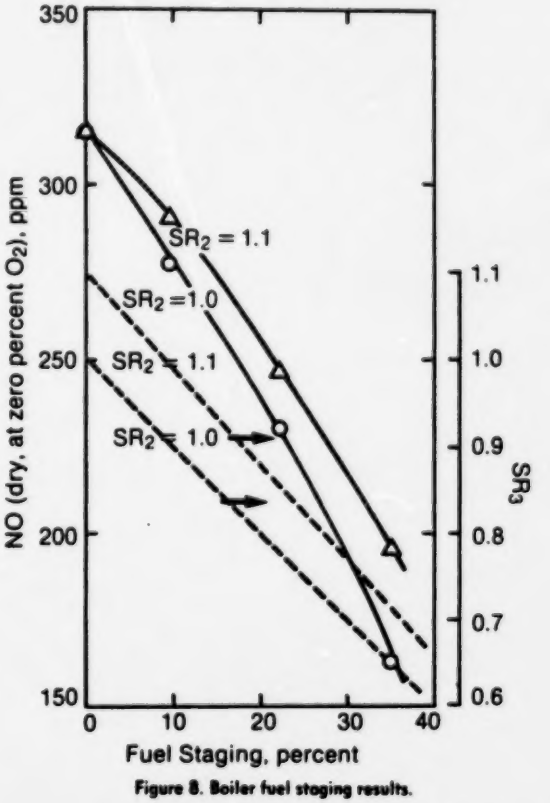


Figure 8. Boiler fuel staging results.

Boiler Fuel Staging Results

As in the tests just described, total boiler load was held constant while fuel was diverted from the primary fuel injector to a secondary injector. In this case, the staged fuel (undoped natural gas) was injected into the boiler downstream of the secondary radial air addition. Thus, a four-stage combustion process is established, consisting of a fuel-rich burner zone and three boiler zones characteristic of reburning (i.e., fuel-lean, fuel-rich, fuel-lean). As already described, all of the staged air and fuel flows were injected from the front face of the boiler at various angles, resulting in the three boiler stoichiometric zones. Figure 8 shows that the NO emissions decrease with an increase in fuel staging. This is due to both primary NO destruction and primary combustion gas dilution. Two second-stage stoichiometries (SR_2) were established: 1.1 and 1.0. With 35 percent fuel staging, the exhaust NO levels were reduced to 195 ppm (from 315 ppm) at a SR_2 of 1.1, and to 160 ppm at a SR_2 of 1.0. Due to less distinct stoichiometric zones than typically established in reburning application and incomplete nitrogen chemistry in the primary flame, the NO reduction by fuel staging is not quite as great as that obtained when the staged fuel is injected farther downstream of the fuel-lean primary combustion zone [*12*]. However, the configuration used in these tests required no boiler penetrations. With this multistaged combustion, the NO_x emission goal of 175 ppm was met. In addition, the complete destruction of the primary fuel/waste stream appears to be ensured by providing all of the required primary combustion air prior to entry into the boiler, and then passing the primary combustion gases through a secondary flame.

DISCUSSION AND CONCLUSIONS

Results from the various combustion modification schemes for the reduction of NO are summarized in Table 1. These results were obtained at optimal first-stage stoichiometries. From the table it can be seen that deep air staging and fuel staging in the boiler are most effective in minimizing NO emissions, with an overall conversion of fuel nitrogen to molecular nitrogen of 98 percent. However, deep air staging not only presents problems of hardware modification due to boiler penetrations, but may also lead to incomplete combustion. On the other hand, the boiler fuel staging hardware modifications used in this study were designed with retrofit feasibility and efficient combustion in mind. In the tests described here, all of the secondary combustion air necessary for primary fuel burnout is introduced with rapid mixing at high temperatures in the water-cooled transition section between the burner and boiler. Further, the staged fuel and air from the front face of the boiler provide a secondary flame for increased primary fuel/waste destruction, similar to incinerator afterburners.

Some mention must be made of the limitations of these results. First, little information has been collected to date on surrogate fuel/waste burnout. Burning natural gas and ammonia mixtures, rather than the liquid and solid fuel/waste mixtures that are encountered in practice, allows for well-controlled parametric testing for NO_x emission evaluation, but it does not provide for good burnout simulation. Stack emissions of CO were less than 10 ppm for every test condition reported here. However, in-furnace sampling provides insight into the potential for fuel burnout problems. Another problem involved in testing with natural gas is the simplified mixing processes and faster kinetics characteristic of gaseous fuel combustion. First-stage fuel nitrogen conversion to molecular nitrogen is expected to be lower for less volatile fuels.

TABLE 1. SUMMARY OF RESULTS

Configuration	Amount	Stack NO ppm (percent reduction)
Baseline		
—Unstaged Burner (N.A.)	—	1000
—Long Low NO_x Burner	600 ms	90 (91)
—Short Low NO_x Burner	250 ms	315 (68)
Low NO_x Burner Characterization		
—Excess Air	5%	290 (71)
—Load	65%	260 (74)
—Fuel Nitrogen	2%	250 (75)
Secondary Air Staging		
—Axial	100%	220 (78)
—Deep	100%	160 (84)
Fuel Staging		
—Burner	35%	190 (81)
—Boiler		
—SR_2 = 1.1	35%	195 (80)
—SR_2 = 1.0	35%	160 (84)

Another limitation of this study is that the results are applicable only in the range of temperatures characteristic of the firetube package boiler. Temperatures in the package boiler simulator range from 1700 K at the boiler entry to 1250 K at the boiler exit. To avoid high thermal NO formation in the primary combustion gas burnout, sufficient heat must be extracted in the transition section to lower the combustion gas temperatures to less than 1800 K.

Finally, note that the low NO emissions from the fuel staging tests are achieved largely by the dilution of the primary combustion gases with secondary flame gases, which do not have a fuel nitrogen input. Actual molar destruction of NO is small in these tests. However, this dilution is coupled with the NO formation and destruction processes and should not be discounted. From the standpoint of NO minimization and fuel/waste destruction maximization, the overall emissions per unit mass of input should be considered. From this perspective, fuel staging in combination with the shortened precombustion chamber burner appears to be the most attractive combustion modification for high nitrogen content fuel/waste firing in boilers.

Further characterization of this multistaged burner design is ongoing at EPA. Fuel burnout is being measured to optimize both combustion efficiency and NO emission. Fuel oil/pyridine test results will be published shortly [*17*].

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